

GREEN MONO PROPULSION ACTIVITIES AT MSFC

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ABSTRACT

In 2012, the National Aeronautics & Space Administration (NASA) Space Technology Mission Directorate (STMD) began the process of building an integrated technology roadmap, including both technology pull and technology push strategies. Technology Area 1 (TA-01) for Launch Propulsion Systems and TA-02 In-Space Propulsion are two of the fourteen TAs that provide recommendations for the overall technology investment strategy and prioritization of NASA's space technology activities. Identified within these documents are future needs of green propellant use. Green ionic liquid monopropellants and propulsion systems are beginning to be demonstrated in space flight environments. Starting in 2010 with the flight of Prisma, a 1-N thruster system began on-orbit demonstrations operating on ammonium dinitramide based propellant. The NASA Green Propellant Infusion Mission (GPIM) plans to demonstrate both 1-N, and 22-N hydroxyl ammonium nitrate (HAN)-based thrusters in a 2015 flight demonstration. In addition, engineers at MSFC have been evaluating green propellant alternatives for both thrusters and auxiliary power units (APUs). This paper summarizes the status of these development/demonstration activities and investigates the potential for evolution of green propellants from small spacecraft and satellites to larger spacecraft systems, human exploration, and launch system auxiliary propulsion applications.

INTRODUCTION

MSFC has a history of taking propulsion systems from mid-level technology readiness levels (TRL) to flight systems as shown by Figure 1. Of recent interest to the Agency is the development of green propulsion. Between 2004–2009, MSFC was instrumental in liquid oxygen/liquid methane cryogenic green propulsion components, subsystems and systems.^{3,4} Following this activity, focus moved into green mono propulsion applications to complement and perhaps replace hydrazine use.

Hydrazine has an extensive >50-year history and is commonly used for reaction control system (RCS) thrusters, apogee thrusters and APUs. However, the propellant is toxic and requires hazardous operations procedures. Efforts in Sweden and in the United States with the Air Force Research Laboratory (AFRL) have shown progress in the development of green monopropellant alternatives to hydrazine.

Assessing the green propellant applications and technology needs, MSFC has defined five different categories of pursuit: small thrusters (<1

N), mid-sized thrusters (~22 N), large thrusters (~440 N), APUs, and advanced pressurization. These categories are further explored in terms of the space applications and will be discussed further. There is a separate paper during the Space Propulsion 2014 conference that is focused on APU.⁵

MSFC views the upper end of thrust class to be 100 lbf (440 N) for hydrazine replacement and 200 lbf (880 N) for bi-propellant replacement. The Swedes are introducing a 200-N (~50-lbf) thruster soon for flight. Growth above this level would enable competition with both existing 100-lbf hydrazine and nitrogen tetroxide (NTO)/monomethyl hydrazine (MMH) bi-propellant 100-lbf thrusters. There have been over 320 engines built in the 50-lbf thrust class and another 50+ in the 100-lbf class with hydrazine. Although the Viking and Curiosity landers to Mars flew 700-lbf (3114-N) thrusters, that thrust application is extremely limited in use. There are diminishing returns from a propulsion system trade perspective to go above 100 lbf due to NTO/MMH performance. However, there have been over 800 R-4D thrusters built and an-

In-Space Propulsion Experience Base



Spacecraft or System Name	Most Recent Activity*	Human Rated	Biprop (MMH/NTO)	Mono-prop (N2H4)	Oxygen/ Methane	Hydrogen Peroxide, JP-8	Dual Mode	Cold Gas	Non-Toxic	Cryogenic
Robotic Lunar Landcr	Ongoing	No	● (MMH/MON-25)							
Orion Service Module Propellant Tanks	Ongoing	Yes	●							
Chandra	Flying	No	●	●			●			
Ares I Upper Stage ReCS	Ongoing	Yes		●						
Ares I First Stage RoCS	2010	Yes		●						
Ares I-X First Stage RoCS	2009	No	●			●				
PCAD LO2/LCH4 Engine	2008	No				●			●	
Demonstration of Automated Rendezvous Technology (DART)	2005	No		●						
NGLT LO2-Ethanol thruster	2005	No							●	●
In-House 25-lbf O2/CH4 Thruster	2005	No			●				●	●
Orbital Space Plane	2004	Yes	●	●						
X-37 Orbital Vehicle (2nd version)	2003	No	●							
X-38 Deorbit Propulsion	2002	No		●						
NGLT LO2-LH2 Thruster	2002	No							●	●
X-37 (Original version)	2001	No				●	●		●	
US Prop Module (for International Space Station (ISS))	2000	Yes	●							
X-33 Reaction Control System (gaseous O2/CH4)	2000	No			●				●	
Interim Control Module (ICM) for ISS	1998	Yes	●							
Aeroassist Flight Experiment	1994	No		●						
Combined Radiation and Release Effects Satellite	1991	No			●					
Orbital Maneuvering Vehicle (OMV)	1990	No	●	●						
Inertial Upper Stage RCS; Transfer Orbit Stage RCS	1990	No		●						
HEAO (3 spacecraft)	1981	No		●						
Skylab	1977	Yes						●		
Saturn S-IVB Auxiliary Propulsion System	1973	Yes	●							

Figure 1. MSFC has a long history with in-space propulsion, from Saturn V to current work on Orion and SLS.

other 70+ Leros engines in the 100-lbf class. There is an ample market for potential replacement of thrusters across a variety of spacecraft applications.

Nanosatellites, CubeSats, and small satellites are beginning to show interest in use of green mono propulsion thrusters up to 1-N class. General spacecraft (<500 kg) lean more toward the 22-N to 50-N class for apogee engines and lower thrust classes for RCS applications. Larger spacecraft (>500 kg) and robotic exploration vehicles will be the upper end of thrust class (440 N). Lastly, human exploration and launch systems would be interested in 440-N class thrusters from a human-rated spacecraft RCS and roll control for launch vehicles.

MSFC review of potential green propellants is centered on 4 different options. First is the Swedish-developed ammonium dinitramide (ADN)-based propellant known as LMP-103S. Second is the AFRL-developed HAN-based propellant known as AF-M315E. Third is nitrous oxide fuel blend experimental (NOFBX) initially developed by Firestar Technologies. Lastly, a 90% concentration of hydrogen peroxide (H2O2) is regaining consideration. The remainder of this paper will focus on MSFC efforts in these areas.

MSFC has similar, long history with solid propellants:

- Orion LAM & ACM
- Ares-I motors (USM, BDM, FSTM, BSM)
- STAR motors
- Inertial Upper Stage
- Sounding Rockets

EXISTING EFFORTS

The Prisma satellite is a project lead by the Swedish Space Corporation that consists of two satellites (Mango and Tango) that fly in formation with a mother satellite. It was launched along with the PICARD spacecraft on June 15, 2010, on a Dnepr-1 in Russia. While the primary objective is to test autonomous formation flying, the mother spacecraft also carried 1-N hydrazine and LMP-103S thrusters to show an “apples-to-apples” comparison between the different propellants.

ECAPS, a subsidiary of the Swedish Space Corporation, has continued to expand the thrust classes available with LMP-103S. They are now providing multiple units to Skybox imaging constellation of cube satellites and are scheduled to fly a 200-N thruster soon on an ESA mission.



Figure 2. ATK/ECAPS 22-N thruster.

AFRL, with the assistance of Aerojet, have recently conducted ground demonstrations for 1-N and 22-N AF-M315E thrusters. In 2015, Ball Aerospace Corporation will be flying a small satellite that uses these thrusters to demonstrate on-orbit operations.

In March 2011, the team of Innovative Space Propulsion Systems and Firestar were selected to develop and perform a NOFBX flight experiment at the International Space Station (ISS) in late 2012. Due to a variety of factors, the ISS Program Control Board de-manifested the experiment from upcoming missions and awaits further test data before putting it back on the manifest.

MSFC IN-HOUSE EFFORTS

Current activities at MSFC span from thruster to power generation to pressurization applications. MSFC has procured a 1-N AF-M315E thruster from a vendor located in Huntsville. The testing to be conducted at the MSFC Component Development Area (CDA) will include characterization testing and allows for support staff (technical, programmatic, and safety) to get

hands-on experience. With emphasis being placed on CubeSats, MSFC is investigating use of the 1-N thruster with smaller attitude control thrusters for implementation into a 3U-sized spacecraft. Further design evolutions will look at sub-1U if possible.

MSFC has also procured a 22-N LMP-103S thruster for further checkout testing at the CDA. The author participated in the acceptance testing of the thruster in Grindslon, Sweden, in March 2014. The hardware is scheduled to be shipped soon and will be integrated into the CDA following the 1-N thruster testing currently planned.



Figure 3. Test stand installation at CDA.

Consideration has also been given to tri-gas (or tridyne) thruster maturation. MSFC has spent over 4 years evolving the catalyst material and the subsequent thruster testing. Evaluation is also underway to consider tridyne as a propellant tank pressurant. Other warm gas alternatives, like high-purity hydrogen peroxide and nitrous oxide, are also being reevaluated for use as a spacecraft pressurant. Some amount of low-dollar MSFC independent research and development (IRAD) funds are being provided to address pressurization.

MSFC also works with academia to examine technical issues that face green propulsion advancement into the mainstream. MSFC is mentoring a post-graduate intern from Utah State University who is investigating ionic liquid igniter development. Likewise, MSFC is heavily engaged with small businesses that are investigating other ignition and catalyst enhancement work.

Green Propulsion Roadmap

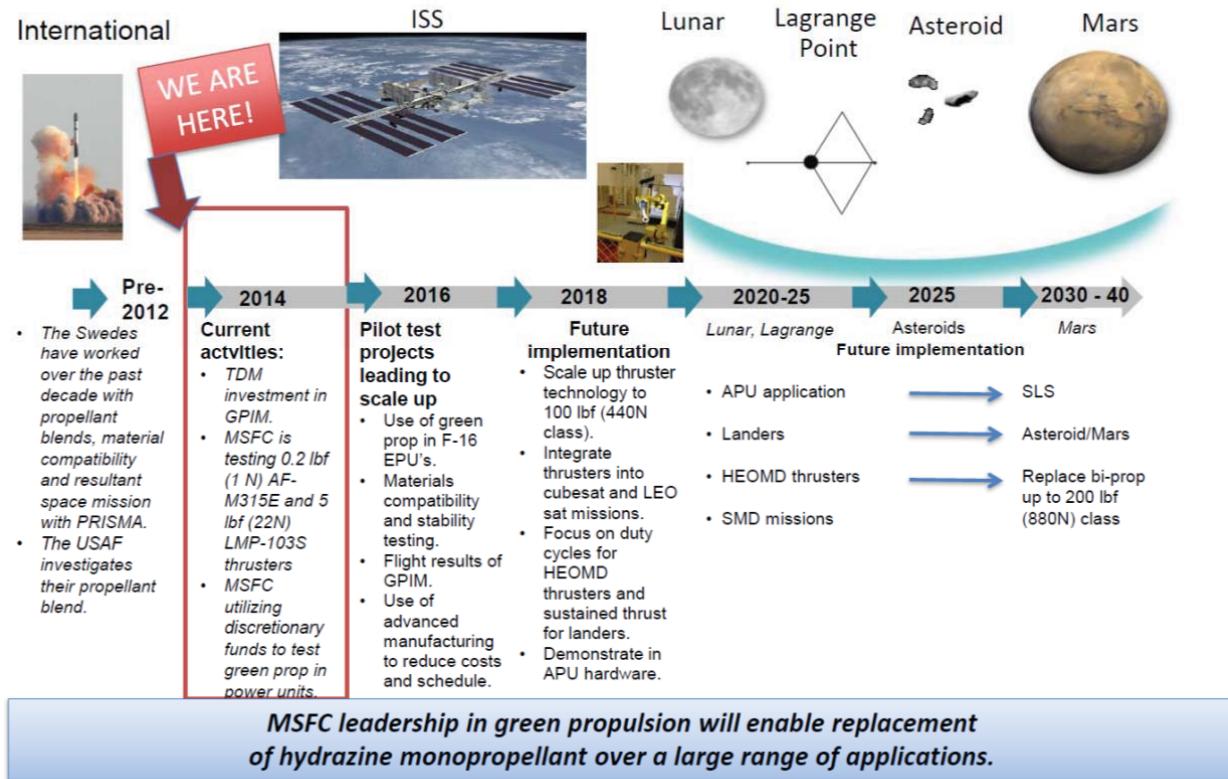


Figure 4. MSFC Green Propulsion Roadmap.

Lastly, MSFC has dedicated some IRAD dollars to invest in green propulsion for use in power generation systems. Shuttle heritage gas generators and auxiliary power units have been retrieved and stand ready for technology development activities. Surrogate hardware has been located to assess feasibility of green propellants with the existing Shell 405 catalyst, currently used for hydrazine systems, to determine reactivity and limitations of use.

MSFC GREEN PROPULSION ROADMAP

In the 4th quarter of fiscal year 2014, MSFC began to develop a green propulsion roadmap. This conference is our first opportunity to roll out what MSFC views as the important next steps to take and will be excited to coordinate international support to meet mutual goals. As was described in Section 4 on in-house efforts, the majority of these efforts can be viewed as pilot projects to obtain empirical data that can lead to more detailed models to understand the catalysis, ignition and other performance and life issues.

The development of the MSFC roadmap focused on the many questions yet to be answered or assumptions that lack confirmation. Examples include evaluating propellant formulation for maximizing purity for spacecraft RCS propellant stability versus relaxation of purity for apogee usage (early mission use compared to prolonged system use) and evaluation of system cost implications. What are the decomposition temperature and stability of these different blends, especially considering the use in APU systems with lower temperature limits for existing systems and components?

Additional questions include: Are existing propellant tank bladder materials adequate for green propellants? Are there ways to minimize (or eliminate) pre-heat requirements on catalyst beds? What causes catalyst wash-outs with green propellants and can it be prevented? How can catalyst life be extended and can we address failure mechanisms and design to reduce or eliminate them?

For consideration into applications for human-rated missions, extensive testing would be required for A/B ratings of materials. Are there

alternative ignition options to catalytic? Lastly, what is the system robustness against deep thermal cycles and gradients? There appears to be a lack of demonstrations involving precipitating and re-dissolving the salts in green propellants.

MSFC envisions future efforts to concentrate in these areas that can be summarized into three categories: material compatibility, life, and scalability. Most notably, there have been concerns on previous testing of M&P characteristics by various DoD and industry counterparts. MSFC aims to re-evaluate and re-perform some of these tests to help mitigate the disagreements. We believe we can make a broad infusion of technology advancements to the industry base, to the DoD personnel, and to our international partners.

Examples of the work MSFC plans to perform to combat the issues identified in our roadmap include materials compatibilities, propellant properties, suitable propellant tank bladder materials, mechanical impact, friction, spark ignition, and thermal stability testing. MSFC would maintain this data in our Materials and Processes Technical Information System (MAPTIS) database, which has been used by multiple program and projects including the International Space Station. The goal of MAPTIS is to provide a single-point source for materials properties for NASA and NASA-associated contractors and organizations. MAPTIS contains physical, mechanical, and environmental properties for metallic and non-metallic materials.

MSFC will pursue an empirical approach in a laboratory setting to evaluate reacting flows. Catalyst bed geometry is irregular and heterogeneous catalysis may require some simplifying assumptions. This effort would evolve into a computational fluid dynamics-based calibrated model for the catalyst bed flow eventually able to simulate with physical calculations. Recent advancements in modeling surface reactions of solid rocket motor ignition would be the starting point for our activities.

Current valves are solenoid, but larger thrusters will need variable position valves. MSFC will review current green propellant formulations and opportunities to evolve them. Initial thermal modeling will build simplified geometry/mesh and apply boundary conditions for a specified

operational timeline (including soak back). Eventually, model growth will include space orientation (thruster facing the sun) and pulse operation. This will aid future mission design in avoiding any potential thermal issues.



Figure 5. Pulsed thruster valve.

MSFC has also made improvements in advanced manufacturing (AM) by producing propulsion components eventually leading to integration into system level assemblies. The use of AM would enhance green propulsion with reduced manufacturing costs, especially for quick turn-around hardware investigations. Lead times are cut an order of magnitude with repeatable manufacturing and the ability to construct complex flow passages. Current MSFC priorities are focused on propellant management devices, chamber/nozzles, and integrated system hardware. This could also be coupled with other entities performing similar work.

With the goal of fostering collaboration with industry and/or international entities, MSFC could test existing green propellant assets through Space Act Agreements or Technical Assistance Agreements. Given limited vacuum test capability at MSFC, we could still place the injector system (head-end) into vacuum conditions to simulate space-like environmental conditions or team with other NASA Centers or international partners for larger facilities. However, the growth to 440-N thrust levels may require a deeper budget commitment from NASA/international development efforts.

Looking at the last 5 years of NASA Science Mission Directorate missions, the majority have required hydrazine propulsion for either apogee and/or RCS functions in the thrust class of 440 N (100 lbf) or less. Beyond the use of green prop

thrusters in these applications, there are recurring missions that could aid future infusion. For instance, the NASA Geostationary Operational Environmental Satellite (GOES) and Landsat spacecraft are prime examples of future constellations along with the transformation of existing buses provided by industry.

In the coming years, there could be the opportunity to transform the NASA Human Exploration and Operations (HEO) Mission Directorate by increasing the number of green propulsion applications. Besides the opportunity to replace hydrazine-fueled APUs for SLS booster nozzle gimbaling, there is potential for replacing roll control thrusters for launch vehicles, RCS for the Orion crew and service module, apogee/RCS on commercial cargo/crew spacecraft (SpaceX Dragon and OSC Cygnus) as well as the ISS resupply vessels HTV and ATV.

CONCLUSIONS

MSFC has a long-standing history of taking lower TRL hardware and maturing them into flight systems. With the SLS managed at MSFC, we aim to infuse green propellant into the launch vehicle. Having ties into both HEOMD and SMD, MSFC also aims on replacing hydrazine and lower thrust bi-propellant systems for various applications. MSFC is at the hub of space transportation for the Agency and invites international participation where there is mutual interest and opportunities to share the workload.

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